AGARDograph 63

Radio Navigation Systems

FOR AVIATION AND MARITIME USE

A Comparative Study

Technical Editor

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CONTENTS

2.02. CONSOL AND CONSOLAN

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1. GENERAL INTRODUCTION

" CONSOL ", the international designation of the German radio navigation aid " Sonne ", was developed from the " Elektra " beacon. This *directional radio beacon* was designed in 1940 with the aim of obtaining a long-range navigation system of high accuracy. Only a modest amount of airborne (shipborne) equipment should be required.[1] The position lines were defined by equisignal zones. Accuracy was increased by the use of a multi-lobe pattern produced by combining the fields of two antennas spaced a few wavelengths apart. Thus a radiation pattern (fan) originated consisting of alternate sectors of dot and dash signals separated by equisignals. The orientation of the equisignal could be adjusted by shifting the phase of the antenna currents, with the restriction, however, that only one equisignal could be aimed to the respective target at a time.

The slow *rotating radio beacon* Sonne was developed from this directional beacon in 1942. In the Sonne system the equisignals and sectors rotate continuously and uniformly in space, consecutively replacing the dot sectors by the dash sectors and vice versa. After each cycle the pattern reverts to its original position. Due to the compulsory coupling of the rotation with the keying facility required for producing the dots and dashes, the instantaneous position of the equisignals relative to the initial position of the fan can be determined by counting the characters received until one equisignal line passes the observer.

The transmission sequence is composed of the navigational (keying) cycle (combination of 60 dot and dash characters), a long dash, the identification signal and a short interval (see Fig. 1 and Table 1).[1,7,14]

Since then the CONSOL system has hardly changed.[2,3,14] All suggestions for modification failed because they were not compatible with the original simplicity of the system that is one of its foremost advantages, as the user requires no special receiver and equipment for reception and evaluation.

A CONSOL ground station employs three aerials sited in a straight line (section 2: description of principle). A slightly modified version with only two antennas, but using the same method as CONSOL for keying and for rotating the equisignal fan, was tested in the U.S.A. 1949–50 under the designation " CONSOLAN " (Radio Set AN/FRN–5).[3,4] Some stations operating on this principle are being installed in the U.S.A., one of them at Nantucket has been in operation since the beginning of 1958[13] and in San Francisco, Cal., since 1960. The Nantucket station belongs to the CONSOL plan proposed in 1956 by a technical committee of the ICAO for the coverage of the North Atlantic with stations in Iceland, Greenland, Canada, the U.S.A. and the Azores. Figure 2 gives one of the maps, showing seven new stations in addition to the existing five European

CONSOL stations. The solid line comprises the area in which the fixing accuracy to be expected is equal to or better than 10 n.m. during daytime and better than 20 n.m. during night-time for 95 per cent of observations taken (see explanation of Fig. 2).

Since 1960 two CONSOL stations have been in operation in Russia in the Arctic Sea region (see table).

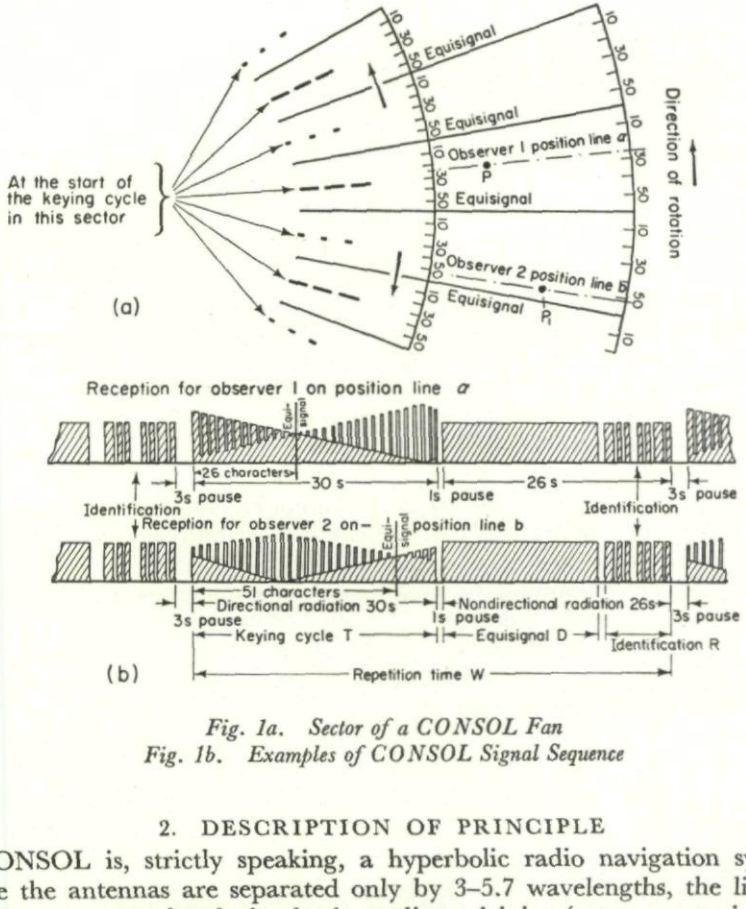

Fig. 1a. Sector of a CONSOL Fan
Fig. 1b. Examples of CONSOL Signal Sequence

2. DESCRIPTION OF PRINCIPLE

CONSOL is, strictly speaking, a hyperbolic radio navigation system. Since the antennas are separated only by 3–5.7 wavelengths, the lines of position are curved only in the immediate vicinity (up to approximately 20 wavelengths distance). At greater ranges they practically coincide with the asymptotes. Therefore, CONSOL is as a rotating radio beacon classified amongst radio navigation systems, which provide radial lines of position.

Because the equal phase lines of a composite radiation pattern are unsuitable for measurements by simple methods, CONSOL employs two alternately shifted patterns produced by a 180° phase keying in a dot-dash rhythm, thus forming the equisignal fan. The slow rotation of the fan is obtained by an additional continuous phase shift of the currents through the two outer antennas.

Station	Geographical Station	Frequency	Main Equisignal	(s. Fig. 1b)	Repetition Time and Number of the Bearing per 10 min.
Bushmills (Ireland)	55° 12′ 20″ N 06° 28′ 02″ W	266 kHz	130 13′	T 30 D 4 R 2	W = 40 Z = 15
Ploneis (France)	48° 01′ 06″ .08 N 04° 12′ 54″ .16 W	257 kHz	106° 12′ 286° 12′	T 30 D R 4	W = 40 Z = 15
Stavanger (Norway)	58° 37′ 31″ N 05° 37′ 40″ 0	319 kHz	067° 247°	T 30 D 19 R 4	W = 60 Z = 10
Lugo (Spain)	43° 14′ 53″ .29 N 07° 28′ 53″ .89 W	285 kHz	088° 30′ 268° 30′	T 30 D 18 R 4	W = 60 Z = 10
Sevilla (Spain)	37° 31′ 17″ .44 N 06° 01′ 48″ .06 W	315 kHz	083° 263°	T 30 D 19 R 4	W = 60 Z = 10
Kanin (Russia)	68° 38′ 18″ N 43° 23′ 30″ 0	269 kHz	175.5°	T 30 D 10 R 6	W = 60 Z = 10
Rybacij (UdSSR)	69° 45′ 12″ N 32° 55′ 0″ 0	363 kHz	25°	T 30 D 10 R 6	W = 60 Z = 10
Nantucket, Mass. (U.S.A.) CONSOLAN	41° 15′ 35″ N 70° 09′ 15″ W	194 kHz	025° 205°	T 30 D 0 R 7,5	W = 42.5 Z = 13
San Francisco, Cal. (U.S.A.) CONSOLAN	38° 12′ 12″ N 122° 34′ 19″ W	192 kHz	50° 230°	T 30 D 0 R 7,5	W = 42.5 Z = 13

T = Keying cycle D = Equisignal R = Identification
W = Repetition time Z = Number or bearing per 10 min.

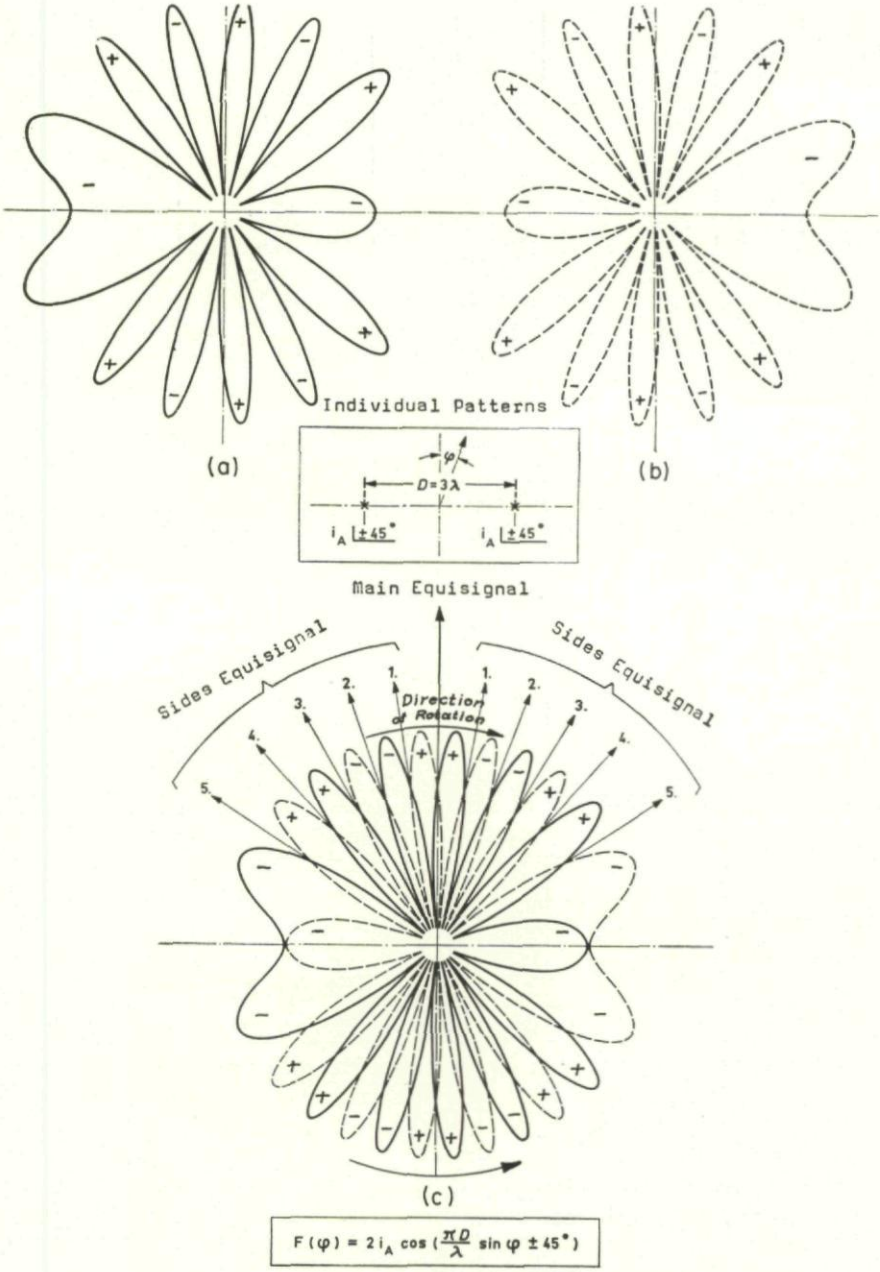

Fig. 3. Azimuth type pattern of a two mast installation, mast spacing $D = 3\lambda$
3a. Phase difference of antenna currents $\varphi = +90°$
3b. Phase difference of antenna currents $\varphi = -90°$
3c. Keying between $\varphi = +90°$ and $\varphi = -90°$ generation of equisignal lines

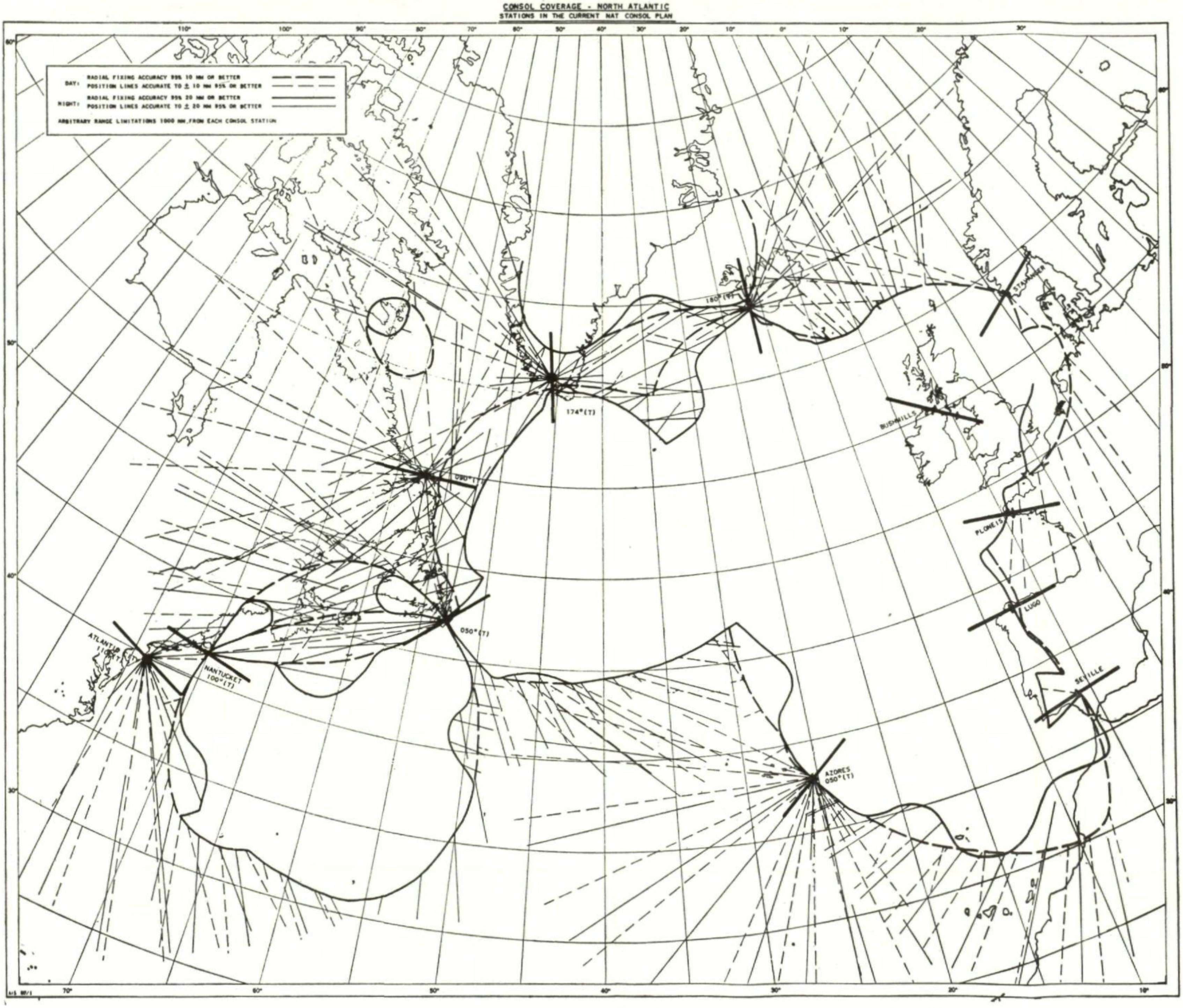

Fig. 2. CONSOL North Atlantic coverage according to " ICAO-CONSOL-PLAN, 1956 ". For CONSOL stations the directions of the main equisignal are shown by a bar (———)*

Estimated range of :x 1000 *n.m.*v

Deviations (95% *probability*) *:*

daytime :x 10 *n.m. within area* — — —

position line 10 *n.m. within area* — — —

night time :x 20 *n.m. within area* ———

position line 20 *n.m. within area* ———

* *The main equisignal of the Nantucket installation was adjusted* 25° *which deviates from the initial planning.*

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In principle only two radiators are required with a spacing of a few wavelengths and fed by the same carrier (Fig. 3).

The phase-keying necessary for obtaining the equisignal fan produces then, however, sudden phase shifts just in the equisignal zone making it considerably wider than desired.[3,5,20]

This disadvantage is avoided when a central radiator, fed with the same carrier, is put between the two outer antennas. The equisignal zones are then formed in those directions where the directive pattern of the two outer antennas approaches zero and only the unkeyed central radiator is effective. The combination of three radiators reduces the number of side lobes by two and the spacing of the outer antennas has to be doubled for obtaining the original configuration.

For a 10° equisignal to the baseline of the three antennas, the distance between the outer radiators is about 6 wavelengths for three-antenna systems and about 3 wavelengths for two-antenna systems.

In the U.S.A. successful attempts were made, at least at long distances, in suppressing substantially the key clicks in the two-antenna CONSOLAN.[20] The r.f. energy is not fed to the towers through an overhead line as is the case with conventional CONSOL stations, but at reduced driving power either by concentric cable or by FM radio link.

This measure was introduced to prevent a horizontal-polarized undesired feeder radiation on the operating frequency, which was supposed to increase the night error. Until now, however, it could not be confirmed that undesired feeder radiation is the reason for the increased bearing error at night, though without doubt this error is caused by a combination of ground and sky waves within the critical range of approximately 400 n.m. from the station. The two towers are fed via phase-stabilized linear amplifiers.

The increase in accuracy by the use of a multilobe pattern leads to an ambiguity of the equisignal zones. For a spacing of about 6 wavelengths between the outer radiators of a three-antenna system the minimum spacing between equivalent sectors is about 20°; the same refers to two-tower CONSOLAN stations with a tower spacing of 3λ. This ambiguity is not objectionable for a long-range navigation system. The sector the observer is actually in, can easily be determined by simple radio direction-finding methods. Besides that, the approximate position will nearly always be known from dead reckoning.

The frequency band of 300 kc/s was chosen at the time of the CONSOL development because it was the common range of the existing receivers, marine and air. Today this range is internationally adopted for radio beacons. Two of the CONSOL stations established after the war operate on about 250 kc/s, two CONSOLAN stations on 190 kc/s (see Table 1). Without doubt the 100 kc/s band would give for CONSOL the same navigational advantage as for other long-range systems. These advantages are larger ground-wave range and more stable reflections from the ionosphere. As, however, the standard airborne and many shipborne receivers have no long-wave range, a special receiver would be required, thus taking away one of the substantial practical advantages offered by CONSOL.

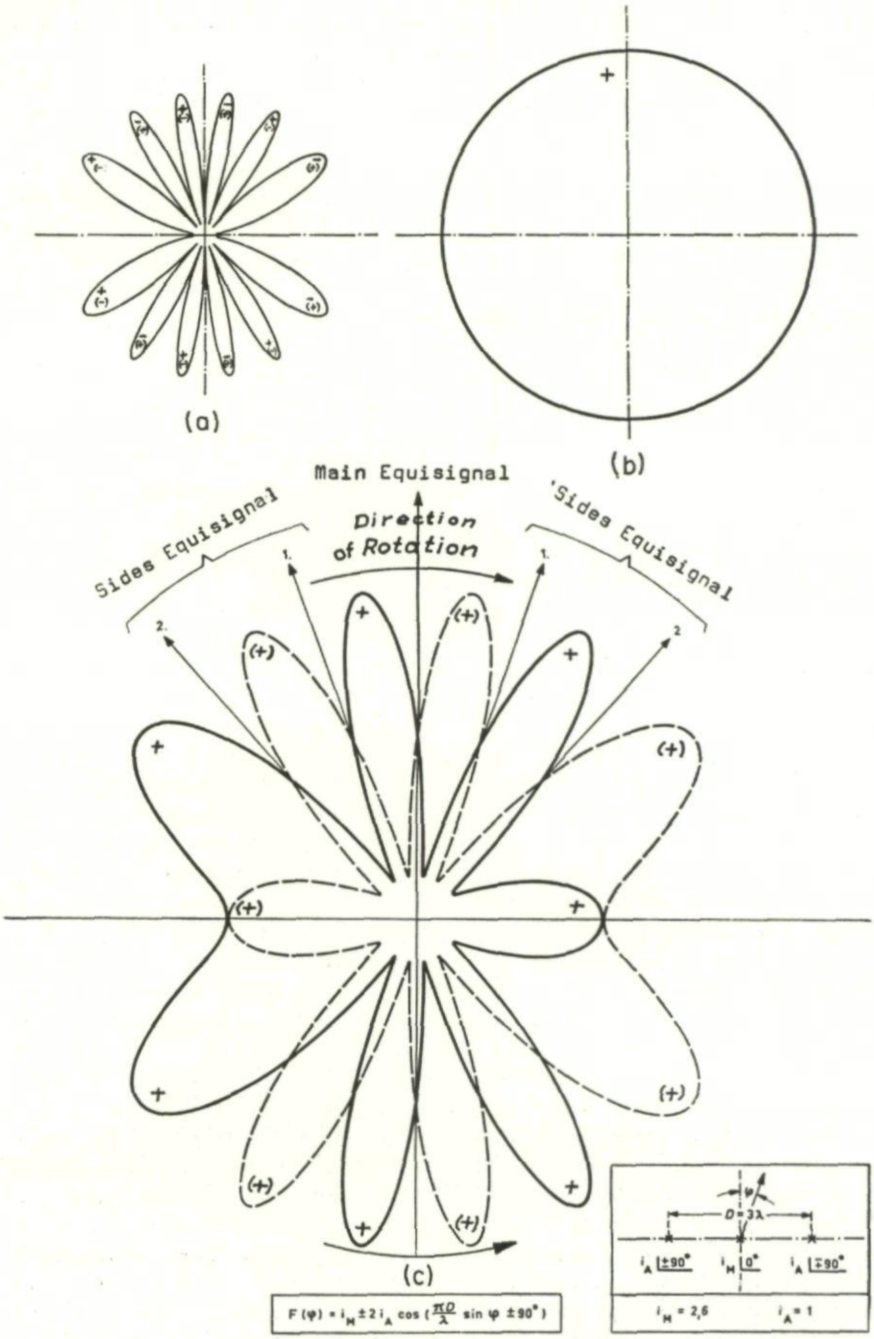

Fig. 4. Azimuth type pattern of a three mast installation, mast spacing $D = 3\lambda$
4a. Side antenna pattern 4b. Central antenna pattern 4c. Combined pattern

3. ACCURACY AND RANGE

The accuracy of CONSOL is limited firstly by the ability of the observer to identify the characters on either side of the equisignal zone, secondly by the number of steps (keyed signals) subdividing the smallest sector.

The limit for aural identification of periodical signals superimposed on a continuous carrier is given at an amplitude ratio of about 5 per cent. From that follows theoretically an observation accuracy of $\pm$ 0.1° within a 10° sector (Fig. 5).

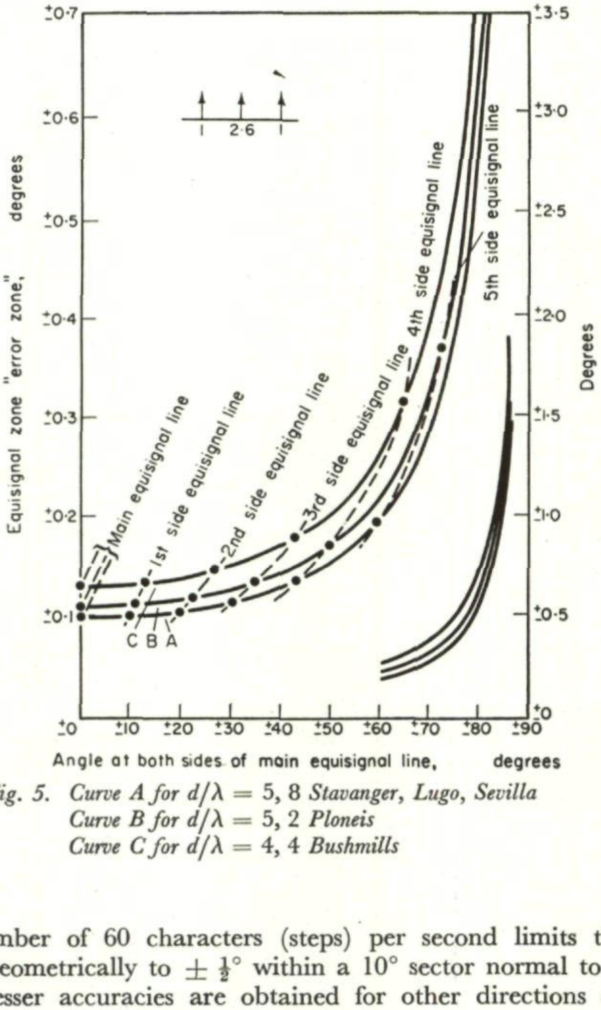

Fig. 5. Curve A for d/λ = 5, 8 Stavanger, Lugo, Sevilla
Curve B for d/λ = 5, 2 Ploneis
Curve C for d/λ = 4, 4 Bushmills

The number of 60 characters (steps) per second limits the possible accuracy geometrically to $\pm \frac{1}{2}$° within a 10° sector normal to the line of aerials. Lesser accuracies are obtained for other directions due to the increasing width of the sectors proportional to the angle from the normal. The decrease in accuracy corresponds directly to the width of a sector. Under average atmospheric noise conditions the standard deviations observed are greater than those following from the system geometry.[9]

The practical values for daytime operation are:

for 50 per cent of the observations $\pm 0.2°$ corresponding to 0.3 per cent of the distance,

for 95 per cent of the observations $\pm 0.6°$ corresponding to 1 per cent of the distance.

The values are valid for ground-wave propagation that prevails also during night-time for distances up to 200 n.m. At distances between 200 and 450 n.m., especially at night, bearing fluctuations occur due to the interference of sky and ground waves. Sky-wave correction curves were published by British authors.[3]

The corrections read therefrom have to be applied to the arithmetic mean value of several observations. These calculated curves show a maximum for the correction at about 400 n.m. depending on the azimuth referred to the normal to the line of aerials. The thus estimated night error is about 3 characters between 10° and 25°, 6 characters between 26° and 45° and 8 characters between 46° and 70°. Beyond 450 n.m. where the sky wave is dominating, the accuracy increases again up to values similar to those valid for undisturbed ground-wave propagation.

A theory of this problem was given by Kümmich: "Der Nachteffekt bei dem Navigationsverfahren CONSOL"[10] (the night error and its influence on the navigation system CONSOL). According to this theory the correction factors mentioned above and the r.m.s.-errors (standard deviation σ) have approximately the same angle and distance dependence. The magnitudes of both are also about the same. Systematic measurements of the frequency and the magnitude of these deviations were made during recent years by the Deutsches Hydrographisches Institut (DHI) (German Hydrographic Institute) for some sectors in the service area of operating CONSOL stations.[16] The objective of these measurements is the practical investigation of theoretical correction curves and standard deviations. The work is not yet completed.

Other publications[11] indicate the following standard deviations for 95 per cent of the observations: At day ± 1, at night between ± 1 and ± 2 characters. The night values apply within distances between 20 and 150 n.m. and beyond 550 n.m. Between 250 and 450 n.m. deviations of ± 4 to ± 7 characters may occur with a maximum at 350 n.m.

Keeling[12] used the following standard deviations as basis for range vs. accuracy curves:

at day on sea	1	character	for all distances
at night on sea	1	,,	from 0–100 n.m.
	2	,,	,, 100–200 n.m.
	3½	,,	,, 200–300 n.m.
	6½	,,	,, 300–400 n.m.
	6	,,	,, 400–500 n.m.
	3½	,,	,, 500–600 n.m.
	2	,,	around 600 n.m.
	1		considerably more than 600 n.m.

For further tables with data gained by experience see ref. 17; an evaluation of approximately 150,000 observations made on two German Sonne installations (propagation over land) was made in England after the war

and published together with extensive own investigations over land and sea.[18]

The maximum useful range of CONSOL is dependent on the propagation conditions (across sea or across land), the atmospheric noise level and the receiver bandwidth. For these reasons the published values show considerable variations. This is also due to the differences in the definition of the term " range ".

Average values:

across sea:	at day	700–1200 n.m.
	at night	700–1500 n.m.
across land:	at day	500–700 n.m.
	at night	900–1200 n.m.

The keying cycle of CONSOL is very slow (at present generally 60 characters within 30 sec). Therefore narrow bandwidth receivers can be used to improve considerably the signal-to-noise ratio and, hence, the useful range. This was proven by French experiments: Ranges of up to 2600 n.m. were obtained with a special receiver of only 100 c/s bandwidth.[6,22,23]

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The radio coordinates supplied by CONSOL are radial lines of position with true reference direction. The indication is not continuous, but has to be determined periodically by counting the number of characters until the equisignal zone is observed every 60 sec (older equipment) or every 45 sec (modern equipment) corresponding to the keying cycle (cf. table). The geographical position is obtained from special maps overprinted with position lines corresponding to selected CONSOL counts or from auxiliary tables.[14] A fix is determined by the intersection of the radial position obtained from two CONSOL stations.

For direct air navigation without reference to a map, CONSOL is only suitable in the special case of flying directly to or from a station and keeping the plane on a line with a fixed number of characters.

Concerning the operation of the receiver, care has to be taken only to avoid suppression or distortion of signals by overload. Normally that is avoided by automatic gain control. Besides that, the indication is independent of the field strength or received power. Ambiguities which amount to 20° around the normal to the aerials have to be eliminated either by dead reckoning or by taking the bearing of the station.

A position line is obtained by counting the number of characters which should be observed through earphones. Automatic counters were proposed, but they have not as yet been used in practice.[19]

5. GROUND STATION AND AIRBORNE (SHIPBORNE) EQUIPMENT

CONSOL Ground Station

Normal transmitter, power approximately 1.5–5 kW, with a keying and goniometer unit; three 100 m towers, with counterpoise, installed in a straight line at a distance from each other of approximately 2.8 wavelengths, r.f. energy fed to the outer antennas via overhead lines; monitor

station close to the normal to the line of aerials at a distance of approximately 4 km from the central aerial mast. Information on costs is presented in Table 4.3.

Only engineering information is available on CONSOLAN. Stations operating in the 190 kc/s range have a power of 6 kW per tower; the tower spacing is 3 wavelengths; tower height 200 m with top loading; the counterpoise seems to consist of 120 copper strips of $\frac{1}{4}$ wavelength; the monitoring station is located on the line connecting the towers. For propagation over sea, a field strength of 50 μV/m is obtained at a distance of 1500 km, and of 10 μV/m at 2100 km.

CONSOL Site Requirements

Plane strip of land of approximately 1×6 km for a wavelength of 1.000 m, ground of maximum uniformity 1 km diameter around the individual aerials; aerial mast bases at approximately equal height above sea level.

For CONSOLAN very stringent requirements concerning the ground conductivity and planeness of terrain must be satisfied.

Airborne (Shipborne) Equipment

Normal radio receiver, if possible, provided with bandwidth control down to 200 c/s, receiving aerial and immediate vicinity uncritical, however, preference should be given to vertical aerials.

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